Technology maturation process: The NASA strategic astrophysics technology (SAT) program

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ABSTRACT

In 2009 the Astrophysics Division at NASA Headquarters established the Strategic Astrophysics Technology (SAT) solicitation as a new technology maturation program to fill the needed gap for mid-Technology Readiness Level (TRL) levels (3≤ TRL <6). In three full proposal selection cycles since the inception of this program, more than 40 investigations have been selected, many meritorious milestones have been met and advances have been achieved. In this paper, we review the process of establishing technology priorities, the management of technology advancements and milestones, and the incipient success of some of these investigations in light of the need of future space missions.

Keywords: Strategic Astrophysics Technology (SAT), Space Technology Maturation, and Technology Management

1. INTRODUCTION

"Technology maturation is an essential step for space programs."[1] The need for properly funded space technology maturation programs has been an acknowledged and a recurring demand identified by many space technologists to diverse organizations and communities. In particular, many of the advisory panels to either private organizations or government agencies have manifested their opinions of the crucial importance of technology investments in general, and of technology maturation in particular.

Over the upcoming decades, the astronomical community envisions many ambitious flight missions to continue exploring and probing the universe. These demanding and complex space missions will certainly require technology advances that will assure their feasibility and success. These advances will demand investments proportional to the complexity and scope of these space missions that will tackle astronomy's most difficult remaining questions.

The advancements of technologies or technology maturation are intrinsically tied to the Technology Readiness Level (TRL) categorization. NASA recently updated the definition of TRL and, since 18 April 2013, the official document that contains these descriptions is the systems engineering process NASA Procedural Requirements (NPR) 7123.1B, Appendix E[2].

The need for technology maturation programs is imposed by the entrance requirement for proposing flight missions, which demands TRL 5 for most, if not all, the critical components so they can be integrated in a timely and efficient manner into a flight prototype. The achievement of technology maturity of instruments and space components can directly reduce the cost and risk of space missions. This was one of the main conclusions of the study published by the US Government Accountability Office (GAO) assessing 21 large NASA projects with a combined life-cycle cost in excess of $43 billion. Most of the projects reviewed by GAO *"did not meet technology maturity and design stability best practices criteria, which, if followed, can lessen cost and schedule risks faced by the project."* [3]

Technology maturation requires advancing hardware and software components toward higher TRL stages, which include validation, demonstration and testing in laboratory and relevant environments. In some cases, the sub-orbital program (i.e., balloons and sounding rockets) can advance the maturity of these components. These maturation activities include dedicated systems testing and component integrations, which are frequently the most expensive activities in the development phases. Therefore, technology maturation is intrinsically more expensive, specific and laborious than technology inception, which, in part, explains the dearth of dedicated funding programs for these activities. On the other

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hand, the ephemeral programs instituted to advance technologies are often the first to be excised from operating budgets since, frequently, they are not immediately connected to a critical or recognized mission or flight program. However, NASA has sponsored successful technology maturation programs in different areas, for example in programs related to the International Space Station[4] and supporting laboratory infrastructure.

Other space agencies, like the European Space Agency (ESA), also require that technologies are at TRL 6 or higher for the mission technology selection process. However, unlike NASA, ESA allows the individual member states to develop technology components that are integrated later in ESA-funded missions. ESA has a technology plan developed in collaboration with the member states; therefore, ESA has the role of coordinating technology development but it does not control the inception of these components.

2. INCEPTION OF THE SAT PROGRAM

In 2009, the Astrophysics Division launched the Strategic Astrophysics Technology (SAT) program to explicitly support the maturation of technologies of mid-range TRL already developed and tested in the laboratory (TRL $\leq$ 3) to a point where they can be incorporated into a flight mission with an acceptable level of risk (TRL 5 or 6). The SAT program was not intended to support basic research of new technologies (TRL 1-3) nor was it intended to support flight qualification of mature technologies (TRL 7-9). SAT is truly intended to fill the so-called "Mid-TRL Gap" of technologies that have potential but are not sufficiently mature, making them ill-suited to be part of flight programs or to be funded under basic research programs. The successful SAT proposers are not required or expected to complete the entire development process during the period of their grants. Rather, the proposers are required to identify verifiable milestones and provide a realistic schedule to achieve these milestones. The technologies emphasized in the SAT program are basically enabling the achievement of science drivers, as opposed to enhancing aspects of further scientific interest.

2.1 Technology Supporting Science Missions

Although the SAT program was instituted a year before the 2010 Astronomy and Astrophysics Decadal Survey[5] was issued, it responds to many space technology recommendations outlined in this report such as the technology development programs for New Worlds, Inflation Probe, and for a future ultraviolet telescope. Furthermore, the definition of space strategic missions, for which the SAT program is intended to develop technologies, primarily represents flight missions that flow from the science priorities and recommendations contained in the Decadal Surveys.

The technology requirements for upcoming missions and the requisite investments for enabling technologies have been studied by NASA Astrophysics. Recent reports, such as the Astrophysics Implementation Plan (2012)[6], explain the rationale of which technologies might be more compelling for investment during the rest of this decade (e.g., technologies with the highest potential for immediate use, technologies that can facilitate partnership with other agencies and/or technologies for missions competing in upcoming the 2020 Decadal Survey). Similarly, but with a longer prospect, the Astrophysics Roadmap (2013) *"Enduring Quests Daring Visions"*[7], lists under notional missions and technologies in Chapter 6, formative era missions and likely technologies necessary to implement them.

The efforts of technology maturation programs are not restricted to the Astrophysics Division within NASA. Within the Science Mission Directorate (SMD), the Planetary Sciences Division, for example, also has a successful program entitled Maturation of Instruments for Solar System Exploration (MatISSE) that supports the advanced development of spacecraft-based instruments that have the potential to become part of future planetary flight missions. Similarly, the Planetary Sciences Division also has a technology innovation program (TRL 1-4) for Planetary Instrument Concepts for the Advancement of Solar System Observations (PICASSO), similar to the Astrophysics Division's Astrophysics Research and Analysis Program (APRA). Likewise, Earth Sciences Division has several technology maturation programs such as the Instrument Incubator Program (IIP), Advanced Component Technology, and the In-Space Validation of Earth Science Technologies.

Moreover, on 21 February 2013, NASA formed the Space Technology Mission Directorate (STMD), which focuses specifically on advancing multipurpose technology across the entire lifecycle, including innovation, development, maturation and flight programs. The STMD portfolio of technology maturation programs (TRL $\geq$ 3) includes Technology Demonstration Missions, Small Spacecraft Technology, Flight Opportunities, Centennial Challenges, and Game Changing Development.

2.2 The Astrophysics Themes

NASA Astrophysics is funded and managed along three strategic themes that respond to three fundamental and enduring questions: 1) How does our universe work? 2) How did we get here? and 3) Are we alone? The answers to these questions lead to the three programs with their own portfolios, missions and activities, namely Physics of the Cosmos (PCOS), Cosmic Origins (COR) and Exoplanet Exploration (ExEP), respectively. Since the technology needs and priorities could be vastly different for each of these themes, the SAT program was organized into three different components as well, each addressing the particular requirements for each theme: Technology Development for Physics of the Cosmos (TPCOS), Technology Development for the Cosmic Origins Program (TCOR) and Technology Development for the Exoplanet Exploration Program (TDEM).

2.3 The First Three Proposal Selection Cycles

The first announcement of opportunity (AO) for SAT proposals was a research element within the ROSES 2009 NASA Research Announcement (NRA). This solicitation was issued only for the TDEM theme and solicited investigations of up to two years. Proposals were due on 28 August 2009, and the first awards were funded at the beginning of the 2010 calendar year. From the beginning, in addition to the standard annual progress reports and final reports, it was required to provide additional information and documentation on milestones, which were to be reviewed by an independent board.

Table 1 presents the proposals submitted for each theme for the three completed proposal cycles. The most recent proposals submitted for SAT 2013 are under review. In the last solicitation the solicited content for TPCOS and TDEM were somewhat restricted (and not solicited for TCOR) explaining the reduced number of proposals submitted.

Table 1. Proposals submitted in the five solicited cycles. Each proposal cycle covers nearly three years; for example, for SAT 2012, the solicitation was released on 14 February 2012, proposals were due on 22 March 2013 and the funding, for selected proposals, commenced during FY 2014.

SAT Element	TDEM/SAT 2009	SAT 2010	SAT 2011	SAT 2012	SAT 2013 (Under review)
TDEM	34	22	Not solicited	17	10
TCOR	_	14	24	13	Not solicited
TPCOS	_	21	26	10	8
TOTAL	**34**	**57**	**50**	**40**	**18**

3. TECHNOLOGY PRIORITIES

The COR and PCOS programs implement a technology-needs prioritization process that consists of analyzing the annual technology gap inputs submitted by individuals and by community groups, then discussing and rating them within the Technology Management Board (TMB) according to pre-determined criteria. Specialists, experts, program scientists and technologists assembled by the program offices form the TMB. This board meets as needed during the course of the year to evaluate and provide feedback on the assortment of technologies that need consideration and analysis. A list of prioritized technologies is produced and compiled in the Program Annual Technology Report (PATR)[8], which is produced for both COR and PCOS as separate volumes. Similarly, the ExEP issues an annual appendix, Exoplanet Exploration Program Technology Plan[9], which contains updates of ongoing technology development efforts supported by the program as well as technology gaps and programmatic priorities.

In Table 2, the priorities for each theme are listed as they were described in the SAT solicitation in the Research Opportunities in Space and Earth Sciences (ROSES) 2012.

4. SELECTED INVESTIGATIONS

Proposals that were responsive and compliant to the SAT solicitations were peer-reviewed and evaluations were supplied for all the investigations. Proposals were recommended for selection based on scientific merit, feasibility, resource allocations and relevance to NASA. The number of selected investigations for full or partial funding is presented in

Table 3. Note that a total of 43 investigations have been selected for funding since the inception of the SAT program: 19 for TDEM, 11 for TCOR and 13 for TPCOS. The overall or historical selection rate of SAT investigations for all three cycles is about 24%, which is on the high side for the current Astrophysics Research & Analysis (R&A) solicitations.

Table 2. Prioritization of technologies for all three themes as described in ROSES 2012, Appendix D.8.

TDEM	TPCOS	TCOR
Starlight Suppression Demonstrations	Technologies for X-ray Astrophysics	Quantum Efficiency (QE) in Detectors
Wavefront Sensing and Control of Scattered Light (+ Detector Development)	Technologies for Gravitational Astrophysics	Optical Coatings
System Performance Assessment	Technologies for CMB Polarization Measurements	Precision Large Optics, Heterodyne Receivers and Cryocoolers

Table 3. Number of investigations selected in the four solicited cycles for each theme.

SAT Element	TDEM/SAT 2009	SAT 2010	SAT 2011	SAT 2012
TDEM	7	9	Not solicited	3*
TCOR	_	3	5	3
TPCOS	_	5	5	3
TOTAL	**7**	**17**	**10**	**9**

*Note. As part of the latest recommendations for funding, six additional proposals were selected among TDEM submissions. Because of their unique relevance to coronagraphic technology, the WFIRST/AFTA Study Office directly funds them.

In Figure 1, the same number of selections as presented in Table 3 for each theme for the first three full cycles of the SAT program, is displayed against technology priorities as they are described in Table 2.

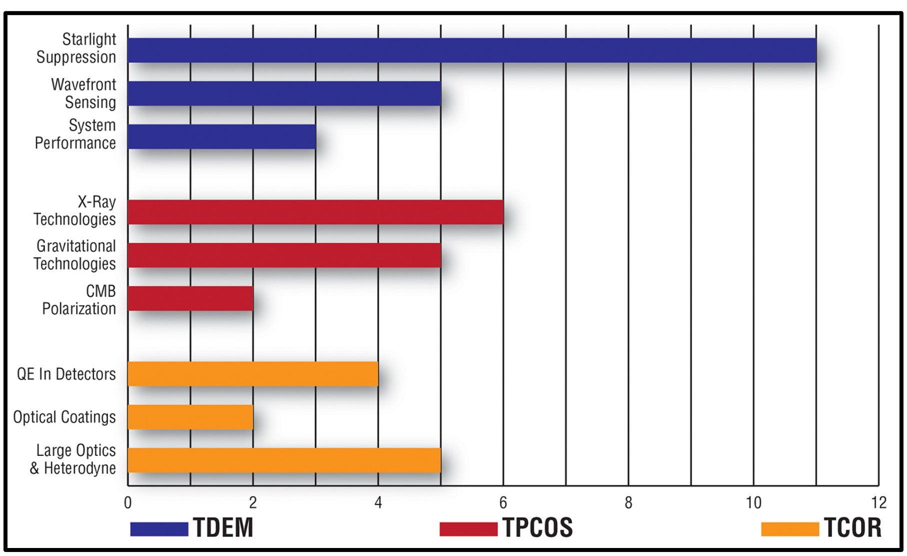

Figure 1. Number of selected SAT proposals for technology priorities within each theme.

In Tables 4, 5 and 6, the selected investigations for each theme are listed according to the year that they were selected. We note that all of this information is public and associated abstracts for these investigations are available via NASA's proposal management portal NSPIRES.

Table 4. TDEM investigations selected in the three completed cycles, including titles, names of the PI, institutions, duration and area within the priorities solicited.

Funding	Technology Development Title	PI	Institution	Start Year and Duration	Area
TDEM2009	Visible Nulling Coronagraph Technology Maturation: High Contrast Imaging & Characterization of Exoplanets	M. Clampin	NASA GSFC	FY10, 2 years	Starlight Suppression
TDEM2009	A Photon-Counting Detector for Exoplanet Missions	D. Figer	Rochester Inst. of Tech.	FY10, 2 years	Detector Development
TDEM2009	Phase-Induced Amplitude Apodization Coronagraphy Development and Laboratory Validation	O. Guyon	U. Arizona	FY10, 2 years	Starlight Suppression
TDEM2009	Starshades for Exoplanet Imaging and Characterization: Key Technology Development	J. Kasdin	Princeton U.	FY10, 2 years	Starlight Suppression
TDEM2009	Assessing the Performance Limits of Internal Coronagraphs Through End-To-End Modeling	J. Krist	JPL	FY10, 2 years	System Modeling
TDEM2009	Advanced Speckle Sensing for Internal Coronagraphs and Methods of Isolating Exoplanets from Speckles	C. Noecker	Ball Aerospace	FY10, 2 years	Wavefront Sensing/Control
TDEM2009	Advanced Hybrid Lyot Coronagraph Technology for Exoplanet Missions	J. Trauger	JPL	FY10, 2 years	Starlight Suppression
SAT2010	Advances in Pupil Remapping (PIAA) Coronagraphy: Improving Bandwidth, Throughput and Inner Working Angle	O. Guyon	U. Arizona	FY12, 2 years	Starlight Suppression
SAT2010	Verifying Deployment Tolerances of an External Occulter for Starlight Suppression	J. Kasdin	Princeton U.	FY12, 2 years	Starlight Suppression
SAT2010	Compact Achromatic Visible Nulling Coronagraph Technology Maturation	R. Lyon	NASA GSFC	FY12, 2 years	Starlight Suppression
SAT2010	Visible Nulling Coronagraph (VNC) Technology Demonstration Program	J. Sandhu	JPL	FY12, 2 years	Starlight Suppression
SAT2010	Demonstrations of Deep Starlight Rejection with a Vortex Coronagraph	G. Serabyn	JPL	FY12, 2 years	Starlight Suppression
SAT2010	Coronagraph Starlight Suppression Model Validation: Coronagraph Milestone #3a	S. Shaklan	JPL	FY12, 2 years	System Modeling
SAT2010	Integrated Coronagraph Design and Wavefront Control Using Two Deformable Mirrors	J. Kasdin	Princeton U.	FY12, 2 years	Wavefront Sensing/Control
SAT2010	Environmental Testing Of MEMS Deformable Mirrors for Exoplanet Detection	M. Helmbrecht	Iris AO, Inc.	FY12, 2 years	Wavefront Sensing/Control
SAT2010	MEMS Deformable Mirror Technology Development for Space-Based Exoplanet Detection	P. Bierden	Boston Micromachines	FY12, 2 years	Wavefront Sensing/Control
SAT2012	Starshade Stray Light Mitigation through Edge Scatter Modeling and Sharp-Edge Materials Development	S. Casement	Northrop Grumman	FY14, 2 years	System Modeling
SAT2012	Demonstration of Starshade Starlight-Suppression Performance in the Field	T. Glassman	Northrop Grumman	FY14, 2 years	Starlight Suppression
SAT2012	Optical and Mechanical Verification of an External Occulter for Starlight Suppression	J. Kasdin	Princeton U.	FY14, 2 years	Starlight Suppression

5. TECHNOLOGY MANAGEMENT PROCESS

The three different astrophysics themes have associated Program Offices that assist NASA Headquarters in the performance of science, research and technology activities for each theme. The PCOS and COR Program Office resides at NASA Goddard Space Flight Center (GSFC) while the Exoplanet Program Office resides at Jet Propulsion Laboratory (JPL). The following sections include the approaches, methodologies and processes for the technology management of the SAT portfolios of each Program Office.

5.1 PCOS and COR Technology Management Process

The PCOS and COR Program Office at GSFC serves as the implementation arm for the Astrophysics Division at NASA Headquarters for both PCOS and COR program-related activities. The Program Office is responsible for managing the strategic technology development awards from the SAT program, namely the TPCOS and TCOR elements.

A diagram of the technology development management process conducted for both the PCOS and COR programs is illustrated in Figure 2. The activities are split into the three main technology development phases: identification, maturation, and insertion. In each phase, the major products are identified and keyed to the organization responsible for creating the product. The transition from one phase to the next is governed by the activity that has a double arrowhead pointing from it.

Table 5. TPCOS investigations selected in the three completed cycles, including titles, names of the PI, institutions, duration and area within the priorities solicited.

Funding	Technology Development Title	PI	Institution	Start Year and Duration	Area
SAT2010	Development of Fabrication Process for Critical-Angle X-ray Transmission Gratings	M. Schattenburg	MIT	FY12, 2 years	X-ray
SAT2010	Antenna-Coupled Superconducting Detectors for Cosmic Microwave Background Polarimetry	J. Bock	JPL	FY12, 2 years	CMB
SAT2010	Directly-Deposited Blocking Filters for Imaging X-ray Detectors	M. Bautz	MIT	FY12, 2 years	X-ray
SAT2010	Off-plane Grating Arrays for Future Missions	R. McEntaffer	U of Iowa	FY12, 2 years	X-ray
SAT2010	Development of Moderate Angular Resolution Full Shell Electroplated Metal Grazing Incidence X-ray Optics	P. Reid	SAO	FY12, 2 years	X-ray
SAT2011	Next generation X-ray Optics: High Resolution, Light Weight, and Low Cost	W. Zhang	GSFC	FY13, 2 years	X-ray
SAT2011	Demonstrating Enabling Technologies for the High-Resolution Imaging Spectrometer of the Next NASA X-ray Astronomy Mission	C. Kilbourne	GSFC	FY13, 2 years	X-ray
SAT2011	Colloid Microthruster Propellant Feed System for Gravity Wave Astrophysics Missions	J. Ziemer	JPL	FY13, 2 years	GW
SAT2011	Telescope for a Space-based Gravitational Wave Mission	J. Livas	GSFC	FY13, 2 years	GW
SAT2011	Advanced Laser Frequency Stabilization Using Molecular Gasses ** (co-funded with STMD)	J. Lipa	Stanford	FY13, 2 years	GW
SAT2012	Antenna-Coupled Superconducting Detectors for Cosmic Microwave Background Polarimetry	J. Bock	JPL	FY14, 2 years	CMB
SAT2012	Demonstration of a TRL 5 Laser System for eLISA	J. Camp	GSFC	FY14, 2 years	GW
SAT2012	Phase Measurement System Development for Interferometric GW Detectors	W. Klipstein	JPL	FY14, 2 years	GW

Table 6. TCOR investigations selected in the three completed cycles, including titles, names of the PI, institutions, duration and area within the priorities solicited.

Funding	Technology Development Title	PI	Institution	Start Year and Duration	Area
SAT2010	Advanced UVOIR Mirror Technology Development for Very Large Space Telescope	P. Stahl	MSFC	FY12, 3 years	Optics
SAT2010	High Performance Cross-Strip Micro-Channel Plate Detector Systems for Spaceflight Experiments	J. Vallerga	UC Berkeley	FY12, 3 years	UV Detectors
SAT2010	Enhanced MgF2 and LiF Overcoated Aluminum Mirrors for FUV Space Astronomy	M. Quijada	GSFC	FY12, 3 years	UV Coatings
SAT2011	Ultraviolet Coatings, Materials and Processes for Advanced Telescope Optics	K. Balasubramanian	JPL	FY13, 3 years	UV Coatings
SAT2011	Kinetic Inductance Detector Imaging Arrays for Far-Infrared Astrophysics	J. Zmuidzinas	JPL	FY13, 2 years	Far-IR Detectors
SAT2011	Improvements of the Performance of Near-Infrared Detectors for NASA Astrophysics Missions: Reducing the Sub-1% Detector Effects	S. Anglin	Teledyne	FY13, 1 year	UVOIR Detectors
SAT2011	H4RG Near-IR Detector Array with 10 Micron Pixels for WFIRST and Space Astrophysics	B. Rauscher	GSFC	FY13, 1 year	UVOIR Detectors
SAT2011	High Efficiency Detectors in Photon Counting and Large Focal Plane Arrays for Astrophysics Missions	S. Nikzad	JPL	FY13, 3 years	UVOIR Detectors
SAT2012	Far-Infrared Heterodyne Array Receiver	I. Mehdi	JPL	FY14, 3 years	Far-IR Detector
SAT2012	Advanced Mirror Technology Development Phase 2	P. Stahl	MSFC	FY14, 3 years	Optics
SAT2012	Development of DMD Arrays for use in Future Space Missions	Z. Ninkov	RIT	FY14, 2 years	Optics

5.1.1 Technology Identification Phase

The program technology management process that drives the identification phase works on an annual cycle. The annual process begins with a review of technology gaps that is developed with inputs from the science communities at large and from the PCOS and COR Program Analysis Groups (PAGs). The technology gap review serves as the primary input for the annual technology prioritization task performed by the respective program's TMB. Concurrent with this activity, funded technology developers provide technology development progress reports. These reports are combined with the results of the technology prioritization process to generate the Program Annual Technology Reports (PATRs) for PCOS and COR.

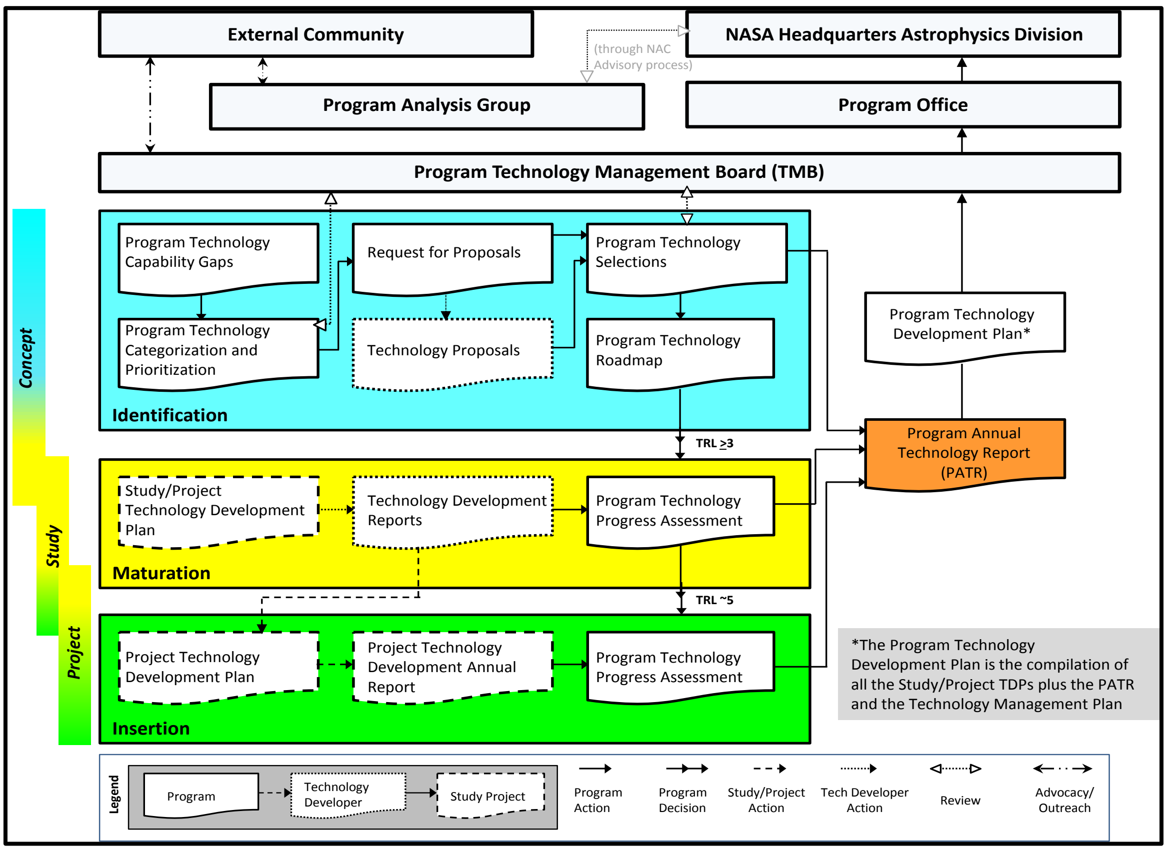

Figure 2. Technology Management Process for the PCOS and COR Programs

The external scientific and technology communities are key stakeholders for the Programs' technology development activities. The community participates in the program technology process in multiple ways, including through the PAGs, workshops held by the program in conjunction with specific studies, and as developers, proposers or reviewers of our solicitations for technology gaps and proposals.

The PCOS PAG (PhysPAG) and the COR PAG (COPAG) are one of the formal mechanisms for including community input into the respective program technology process. The PAGs are open forums, charged by the Astrophysics Subcommittee (APS) of the NASA Advisory Council (NAC) for the purpose of soliciting and coordinating input and analysis from the scientific community. The Program Office customer at NASA Headquarters is the Astrophysics Division. NASA Headquarters PCOS and COR Program Executives, program scientists and discipline scientists participate as TMB members during technology development progress reviews and during the technology gaps prioritization.

The TMBs are program-level functional groups consisting of senior members of the Program Office and NASA Headquarters Astrophysics Division and subject matter experts that enable the direct stakeholders in the technology portfolio to provide input to and review of the program technology development activities. While their members may have line management reporting through separate paths, the TMBs make recommendations to the Program Office and to the NASA Headquarters Astrophysics Division in the areas for which they are responsible. The TMBs are responsible for the prioritization of program technology gaps, oversight and review of the technology development at the program level, and formal input on program-relevant technology issues. The highly prioritized technology gaps for each program are subsequently included in the annual ROSES SAT solicitation to inform and to encourage the community to propose investigations that can fill the gaps. The prioritization is also used to inform the selection of the awards made each year. The selection official for technology development awards is the Astrophysics Division Program Director at NASA Headquarters. The abstracts of selected awards are published in each year's PATRs.

5.1.2 Technology Maturation Phase

The technology maturation phase is entered when a particular technology development effort is awarded. During this phase, the technology developers interact with the Program's Technology Development Manager and the appropriate study/project lead if one was set up. For some missions, the maturation phase will be entirely within the mission study phase and executed by the appropriate study organization. For others, there may be overlap between the study and project phases, and the appropriate project office may take over leading the maturation activities. Technologies awarded for maturation via the SAT program are required to be at TRL 3 or higher. When a mission concept has advanced to the point where a point-design study has been completed, the study team will develop a Study Technology Development Plan (TDP). For some missions, this may be more appropriately done by the project if the mission has advanced to that stage, in which case the project will develop a Project TDP. The TMB reviews and approves the Study/Project TDP. The TMB also reviews and concurs with all milestones identified in the Study/Project TDP including asserted changes in TRL. Program technology progress assessment is performed by the TMB. An annual progress report submitted by each technology developer is included in the appropriate PATR.

5.1.3 Technology Insertion Phase

The technology insertion phase is entered when a particular technology development effort is deemed to be sufficiently mature to be baselined into an upcoming or ongoing project in the pre-formulation or formulation phase. Typically, this will be at or above TRL 5. After insertion, a technology will be further developed according to the project-level technology development plan, as described in NASA Procedural Requirements (NPR) 7120.5. The TMB reviews and approves the Study/Project TDP and, as the Project, reports the achievement of any milestones outlined in their TDP. The Study/Project Technology Development Plans are combined with the PATR and the program's Technology Management Plan to create the Program Technology Development Plan.

5.1.4 Program Annual Technology Reports (PATRs)

As shown in the technology management process flow (Figure 2), the outcomes of the activities of the three phases of technology development for the program are included in the appropriate PATR. These reports provide yearly input to the Astrophysics Division technology development planning process. The PCOS and COR PATRs are publicly released and posted on the PCOS and COR websites each October (http://pcos.gsfc.nasa.gov/technology/ and http://cor.gsfc.nasa.gov/technology/). The objectives are to 1) Inform the SAT solicitation and other technology development program planning; 2) Inform technology developers of the program's technology capability gaps to help focus efforts; 3) Guide the selection of technology awards to be aligned with program goals and science objectives; 4) Improve the transparency and relevance of program technology investments; 5) Inform the community about, and engage it in, our technology development process; and 6) Leverage the technology investments of external organizations by defining capability gaps and where NASA could be a potential customer.

5.2 The Exoplanet Program Office Technology Management

The Program Office of the Exoplanet Exploration Program (ExEP) is located at JPL, Caltech, and manages all exoplanet science and technology activities on behalf of the Astrophysics Division of NASA. The Program has as its long-term science goal the search for habitable planets and the discovery of life elsewhere in the universe. In this effort, the Program is closely guided by specific recommendations from the Decadal Survey.

The 2010 Astronomy and Astrophysics Decadal Survey[5] recommended the creation of a New Worlds Technology Development Program to advance the technological readiness of the three primary starlight suppression architectures: coronagraphs, starshades, and interferometers. The Decadal Survey further recommended—if the scientific groundwork and design requirements were sufficiently clear—that an architecture downselect should be made mid-decade, and a significantly increased technology investment over the latter half of the decade should be focused on preparing a mission concept based on this architecture for consideration by the 2020 Decadal Survey.

"Thus the plan for the coming decade is to perform the necessary target reconnaissance surveys to inform next-generation missions while simultaneously completing the technology development to bring the goals within reach." (NWNH, p. 39)

The goal of exoplanet technology development is to enable future missions by demonstrating selected key technologies. The greatest emphasis is therefore placed on starlight-suppression technology to enable the detection of Earth-like planets around Sun-like stars. This effort must include the establishment of performance error budgets tied to flight requirements and experimental demonstrations that the error budgets, or key components of the error budgets, can be met. Furthermore, models must be validated that demonstrate that the physics of the limiting error sources in those experiments are understood well enough to reliably predict the performance of the flight mission.

Up until 2014, all exoplanet technology development within ExEP has been competitively awarded through the SAT-TDEM program. Beginning in 2014, this effort is being complemented by the direct funding of the development of a coronagraph instrument for the AFTA-WFIRST Project.

5.2.1 TDEM Technology Priorities

The recommendation by the Decadal Survey was to continue to pursue the development of coronagraph, external occulter, and interferometer technologies to allow an architecture downselect by the late-Decade. Nevertheless, for both cost and technical readiness reasons, infrared interferometry is currently of lower priority as the basis for a New Worlds Mission than either of the coronagraph or starshade architectures.[10]

The technology gaps for coronagraphs and starshades are listed in priority order elsewhere.[11] The priority is largely determined by the chronological step-wise development that is needed to bring these systems up to TRL 6. The technology gap lists are revised by the Program Office with input from the community as part of the revision of the ExEP Technology Plan, typically in late summer and early fall.

The NASA Astrophysics Implementation Plan includes studies for exoplanet probe-scale missions as possible alternatives. In 2013–2014 the teams involved in these efforts are developing detailed observatory and mission designs, as well as an independent list of technology gaps and priorities. The interested reader is encouraged to consult the reports generated by these teams when they become publicly available. TDEM is primarily directed at supporting technologies for the development of exoplanet coronagraphs and starshades, with an emphasis on enabling specific future missions. In the context of efforts in this decade, the missions under consideration are probe-scale coronagraph, probe-scale starshade missions, and the AFTA-WFIRST coronagraph. As previously noted, the AFTA coronagraph is being developed with directed funding and so proposals related to its development are not being solicited in the TDEM call. TDEM proposals should address the technology needs of other identifiable mission concepts and not be duplicative of efforts being undertaken for AFTA.

Considering the limited available resources, exclusions are listed in the latest TDEM solicitation in ROSES 2013 to help guide proposers. In particular coronagraph technologies specific to the AFTA aperture, being advanced through the AFTA-WFIRST technology development effort, are not eligible for funding through the SAT solicitation. Technologies that are not eligible include: (1) Masks/apodizers for Shaped-pupil, Hybrid Lyot, and Phase-Induced Amplitude Apodization Complex Mask (PIAA-CMC) coronagraphs; (2) Low-order wavefront sensing and control; (3) Data post-processing; and (4) System-level performance demonstration and modeling of AFTA obscured aperture systems. All SAT/TDEM investigations that propose high-contrast imaging demonstrations are now required to perform both predictive and post-test validated modeling as part of their effort. In the interests of consistency and comparability, investigators will be expected to make use of the ExEP's existing modeling capability.

5.2.2 The Milestone Evaluation and Approval Process

After each cycle of awards, the program works individually with each SAT-TDEM PI to establish one or more formal milestones for their mid-level TRL research efforts. The PIs document their intended objective in a whitepaper that stipulates a performance threshold representing a meaningful advance in technology. The research goals must be traceable to a mission error budget, and model predictions must be based on experimental results. The whitepaper describes the experiment or modeling effort that will be undertaken, specifies the methodology for computing a milestone metric, and establishes success criteria against which the milestones will be evaluated. Amongst these success criteria is invariably a requirement that the technology performance threshold be achieved repeatedly in order to demonstrate the robustness of the technology. The whitepapers are reviewed by the ExEP Technology Assessment Committee and formally approved by the Program. Progress with TDEM-sponsored research is tracked closely by the Program and reported to NASA HQ on a monthly basis. The completion of a milestone is documented in a report by the PI, which is then reviewed and similarly approved. The Milestone Whitepapers that have been completed to date can be found at http://exep.jpl.nasa.gov/technology/.

6. EXAMPLES AND SUCCESSES

Although only three full cycles have elapsed since the inception of the SAT program for all three themes, there is not enough data to derive trends or assess the full success of the program. However, some early successes can be singled out by the recent incorporation of some of these technologies, originally selected competitively through the SAT program, into space missions in formulation. This is the case of the starlight suppression technologies funded by TDEM that competed for the down select process in the internal coronagraph concepts of WFIRST/AFTA for further technology maturation. The WFIRST/AFTA study office has developed a plan for maturing coronagraph technology and retiring major engineering risks by late 2016. Similarly, the new H4RG near-IR (0.7-2.0 μm) detectors that were originally selected and funded by TCOR were also adopted as the detectors to be matured by WFIRST/AFTA for the Wide-Field Imager configuration. Current progress on these detectors, indicate that this technology is capable of producing the required levels of performance for this mission. Within the TPCOS theme, the SAT program supported the development of the antenna-coupled transition-edge superconducting (TES) bolometer, a detector that was fielded in the Background Imaging of Cosmic Extragalactic Polarization 2 (BICEP2) experiment. This technology was central to the Cosmic Microwave Background (CMB) polarization measurements recently reported.[12] The antenna-coupled detector arrays provided a 10-fold increase in measurement speed compared with the BICEP1 predecessor experiment.

Furthermore, due to the TDEM selection of several grants investigating the external occulter for starlight suppression, these technologies have reached important technology milestones such as design, fabrication, deployment and testing, consequently raising the technical maturity of this concept. Because of this progress, a Science and Technology Definition Team (STDT) was appointed in 2013 to consider the possible architecture of an exoplanet probe mission using this technology. A STDT interim report of this activity is now public and is available at: http://exep.jpl.nasa.gov/stdt/.

7. FUTURE OUTLOOK

The technology maturation for SAT funded grants intends to move these concepts along the TRL categorization scheme to make them viable as components in flight mission concepts. Ideally, all selected technology concepts throughout their life cycle maturation path, should become components of technology development within missions under study or development. The natural next step for these technologies is to be adopted as technologies of choice within strategic missions in formulation, and continue their maturation by being sponsored and developed with technology funds allocated for these missions. The successes indicated in this paper have followed this path and it is expected that most, if not all, the investigations selected shall achieve this end point.

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